Viscous modeling of liquefaction-induced settlement of existing structures using dynamic mesh

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Abstract

Seismic liquefaction is commonly observed in most of the large earthquakes. Settlement of structures, especially private houses resting on liquefiable soils has drawn continuous public concerns. The present study deals with the problem of structure subsidence through the framework of computational fluid dynamics. The liquefied ground was simulated using a viscous fluid model. The structure was modelled as a rigid body moving through the computational domain. Dynamic mesh method was used to reconstruct the mesh grid in order to avoid convergence problem due to invalidated meshes caused by structure movement. The volume of fluid method was used for free surface tracking. Furthermore, 1-G shaking table test was performed to obtain the subsidence behavior of a simulated structure resting a liquefied ground. The results showed that settlement of structure obtained from the proposed numerical model was comparable with the measured settlement from shaking table test. It is therefore suggested that the proposed method could be used for assessment of house settlement problems in liquefaction prone regions.

Keywords: Computational Fluid Dynamics, viscous, dynamic mesh, shaking table test, settlement

Introduction

From the most recent major earthquakes, soil liquefaction was substantially observed and its impact to the infrastructures was further recognized, such as the 2001 Arequipa earthquake[1], the 2008 Wenchuan earthquake[2] and the 2011 Tohoku earthquake[3]. Among many liquefaction related damages, e.g. sand boils, ground subsidence, ground cracking and lateral spreading, etc., the subsidence of the existing structures is one of the most intractable problems. Many structures nowadays are built on soft sandy deposits and are therefore potentially prone to liquefaction induced settlement. During the 2011 Tohoku earthquake of Japan, numerous buildings were observed subsided, especially for those structures with shallow foundations resting on the young reclaimed landfills near the Tokyo Bay area[4][5]. Although soil improvements for liquefaction mitigation are often employed in public or industrial projects, it is still not a common practice in residential developments. Damage assessment of such buildings from seismic liquefaction has become an important issue.

During liquefaction, the excess pore water pressure reaches the same value as the effective stress within the soil. The shear resistance of the post-liquefaction soil is substantially reduced to a negligible level. Many laboratory tests have been carried out to investigate the viscous fluid characteristics of liquefied soils[6]-[8]. The viscous description of the liquefied soils has been successfully applied to solve the liquefaction related problems such as lateral spreading[9][10] and large flow deformation[9][10]. For numerical analysis toward the problem of liquefaction-induced structure settlement, however, the studies are limited.

This study concerns with the subsidence of a uniformly weighed structure resting on a post-liquefied sandy deposit. To solve the problem, the liquefied ground was considered as a viscous fluid and the finite volume method was used to realize the division of the computing domain. In previous studies reported by Uzuoka et al. (1998)[9], Hadush et al. (2000)[10] and Huang et al. (2012)[12], only meshes representing the moving fluid deforms. However, during the process of structure subsidence, it becomes the problem of a rigid body moving inside a fluid field. The Rigid mesh of moving structure will compress or drag the meshes within the fluid field and cause negative volume problems. Therefore, the previous fixed meshing method does not apply anymore. To overcome such limitations, a dynamic meshing method is used in the current study. The computing area is re-meshed at certain iteration steps when the preset criteria are satisfied. To verify the proposed method, a 1-g shaking table test was conducted to obtain the structure settlement behavior subjected to ground liquefaction.

Theory for viscous modeling

Viscous modeling of liquefied soil was newly developed in the recent years. The essence of the method is to regard the post-liquefied soils as fluid and use a viscous fluid model (e.g. the Bingham model) to simulate its behavior. The essence of the numerical model is described below.

Governing equation

The process of viscous fluid modeling solves the governing equations through domain partition and mesh generation. In fluid dynamic analysis, the conservation laws are applied to finite control volumes. The continuity equation and the momentum conservation equation can be written as:

$$\frac{\partial \rho}{\partial \boldsymbol{t}} + \nabla(\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial(\rho \boldsymbol{u})}{\partial \boldsymbol{t}} + \nabla(\rho \boldsymbol{u}\boldsymbol{u}) = \nabla \boldsymbol{T} + \rho \boldsymbol{f}_v \tag{2}$$

For Newtonian fluid, the stress tensor $\boldsymbol{T}$ can be written as:

$$\boldsymbol{T} = -(\boldsymbol{p} + \frac{2}{3}\eta \nabla \boldsymbol{u})\boldsymbol{I} + 2\eta \boldsymbol{S} \tag{3}$$

and the Navier-Stokes equation can be written as:

$$\frac{\partial}{\partial \boldsymbol{t}}(\rho \boldsymbol{u}) + \nabla(\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla \boldsymbol{p} + \rho \boldsymbol{f}_v + \nabla \boldsymbol{\tau} \tag{4}$$

where

$$\nabla \boldsymbol{\tau} = \eta \Delta \boldsymbol{u} + \frac{1}{3}\eta \nabla(\nabla \boldsymbol{u}) \tag{5}$$

In the above equations, ρ is the density, t is the time, $\boldsymbol{I}$ is the unit tensor, $\boldsymbol{T}$ is the stress tensor, $\boldsymbol{S}$ is the strain rate tensor, $\boldsymbol{u}$ is the velocity tensor, $\boldsymbol{f}_v$ is the volume force, η is the viscosity, p is the static pressure, $\boldsymbol{\tau}$ is the shear stress tensor.

Dynamic mesh

In the current study, the existing structure lies above the liquefied ground is modeled as a rigid body. During the process of its subsidence, the surrounding ground soils are subjected to deform and move to new positions, resulting in a twisted mesh grid within the computation domain. Convergence problems occur under the most unfavorable conditions when negative volume appears due to invalidated meshes. To overcome such limitation, a dynamic mesh method is adopted in this study by updating the mesh at each time step (or every several time steps) during structure motion. The mesh is updated once the mesh properties meet one of the following criteria: (a) the skewness of a cell is greater than a specified maximum value; (b) the length of an edge is smaller/larger than a specified minimum/maximum length value.

Interface tracking

The volume of fluid (VOF) method developed by Hirt and Nichols (1981)[13] is used for interface tracking. As is mentioned above, the liquefied soil is modeled as a viscous liquid. It is therefore the whole computational domain is filled by two distinct phases: air and liquid. A volume fraction is assigned to each phase within a specific control volume, and the sum of the fractions in the same control volume should be unity (one). In such case, the free surface between the air and the liquid can be constructed based on the volume fraction of each phase. That is, if the liquid's volume fraction in the cell is α_{liq} , then the cell is empty (filled with air) when α_{liq}=0; the cell is full of liquid when α_{liq}=1; and the cell contains the air-liquid interface when0< α_{liq}<1. For cell contains air-liquid interface, the piecewise-linear approach is further used to reconstruct the interface geometry[14].

1-G shaking table test

The model test was conduct on a 1-G shaking table. A rectangular soil container with inside dimensions of 2.0m in length, 0.4m in width and 0.6m in height was mounted on the shaking table. The front side of the soil container was installed with transparent windows to directly observe sand deformation during shaking. The colored sand bars were placed on the side window in both vertical and horizontal direction to construct 10cm×10cm squares, which were helpful for observing sand formation. Fig.1 shows layout of experimental setting.

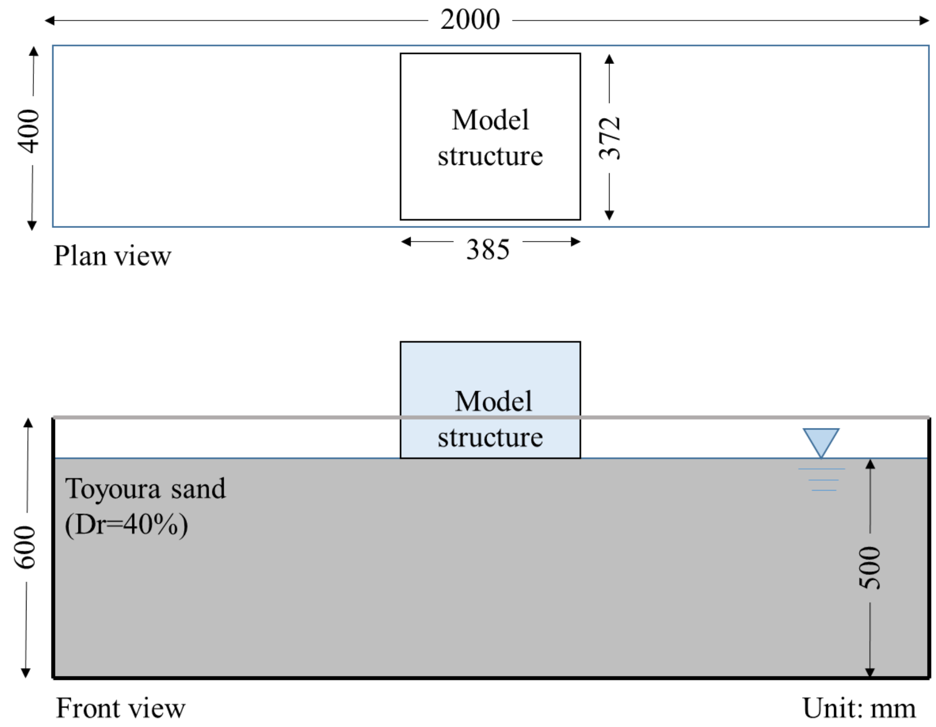


Fig.1 Layout of the shaking table test

The model ground was prepared with water pluviation method. Firstly, water level was risen up to 10cm over the previous layer and then the sand was poured uniformly at a specific height. Toyoura sand was used in the test and the basic properties of the sand are shown in Table 1. A wooden box filled with sand was used to model the surface structure. The base dimensions of the model structure were 38.5cm×37.2cm, which produced a surface pressure of 2.05kPa when the model building was set to 30kg. During the test, the time history of structure settlement was recorded accurately by means of a laser displacement transducer. After finishing the model preparation, a sinusoidal motion of 350 Gal, 10 Hz, and 30 sec was applied to the model.

Table 1 Basic properties of the Toyoura sand

Property	Value
Specific gravity, G_s	2.65
Maximum void ratio, e_{max}	0.98
Minimum void ratio, e_{min}	0.61
D_{50}, mm	0.28
Coefficient of uniformity, Cu	1.30

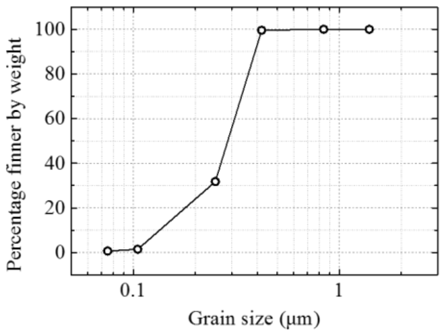
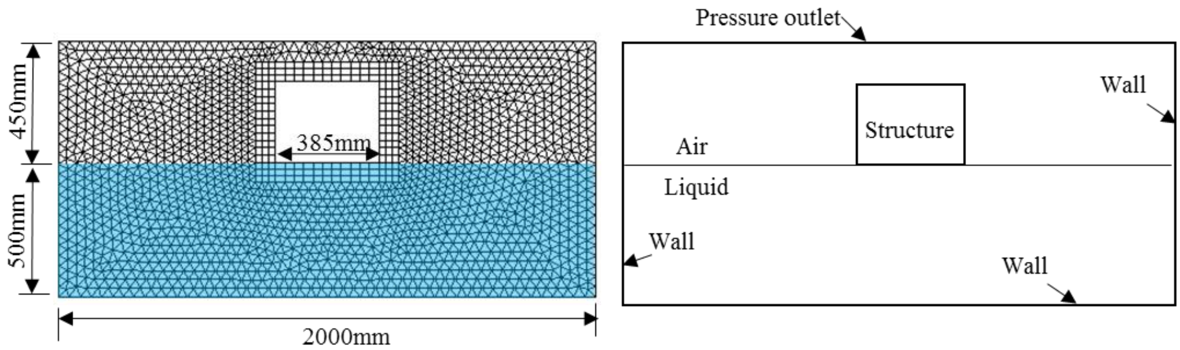


Fig.2 Grain size distribution of the sand

Computational model

The experimental case was further evaluated using the above proposed viscous modelling method. The simulation was implemented in FLUENT software. The schematic arrangements of the model details are shown in Fig.3. Same dimension was adopted with reference to the experimental setup. The existing structure lies one the model ground was modelled as a moving wall and six degree of freedom solver is used for buoyancy and drag force computing. Quadrilateral grids were used as boundary layer for region around the structure, while triangular grids were used for the other regions. When the structure subsidence occurs, the surrounding quadrilateral grids deform synchronously, leading to the deformation of outer triangular grids. Re-meshing is carried out when the specified criteria are met. In total, 1807 nodes, generating 168 quadrilateral cells and 3084 triangular cells, were used at the initial step. The upper edge of the model is set as pressure outlet, with a value of 1.013×10^5Pa. The left, right and bottom edge were set as wall (Fig.3b).



(a) mesh grid (b) boundary conditions

Fig.3 Details of the computational model

Results and discussions

Mesh configuration

Fig.4 show the mesh configurations at different computing time with an interval of 5s. Overall, the updated mesh maintained good quality throughout the whole modelling. The viaration of main paramters of the mesh condition is summerized in Table 2. It is seen that the numbers of toal nodes and cells were approximately the same.

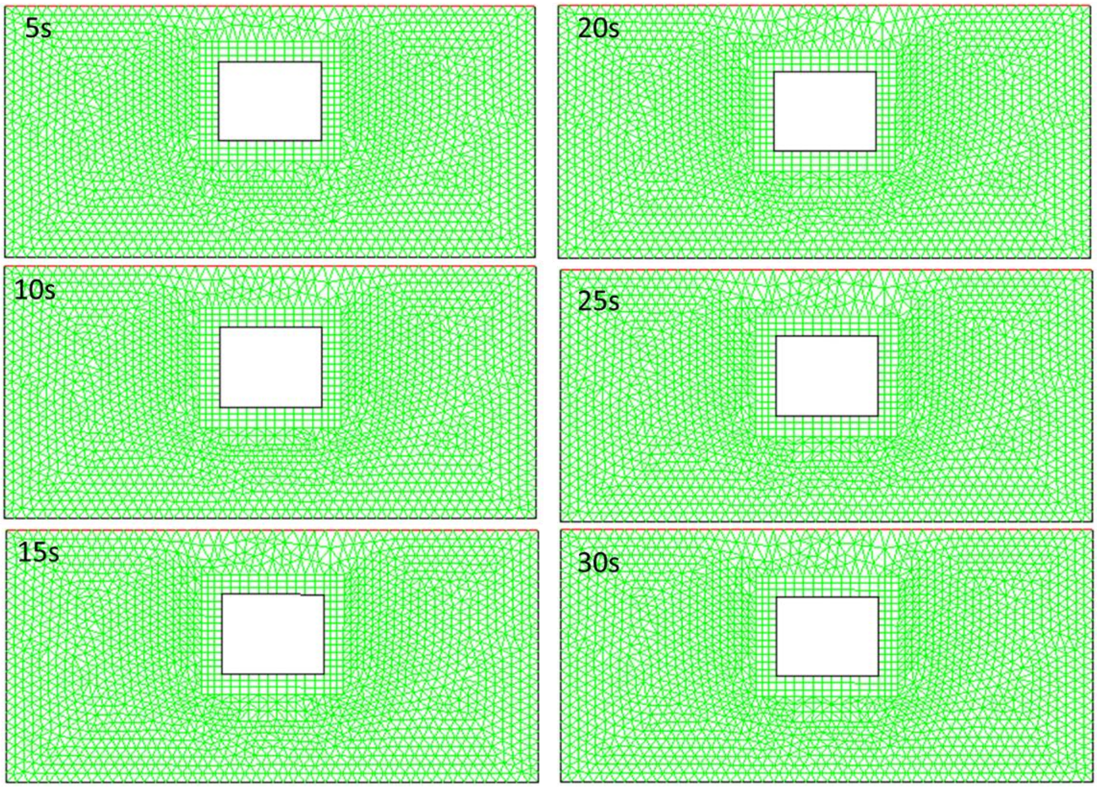


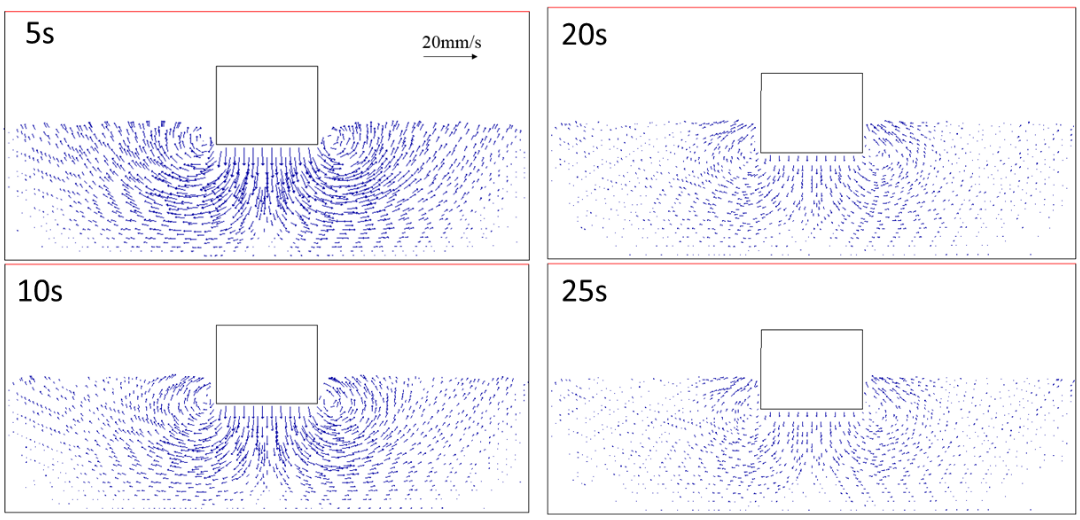
Fig.4 Mesh configurations at different time

Table 2 parameters of mesh grid at different time

Property	Initial	5s	10s	15s	20s	25s	30s
Quadrilateral cells	168	168	168	168	168	168	168
Triangular cells	3084	2928	2952	2942	2944	2948	2950
Nodes	1807	1729	1741	1736	1737	1739	1740

Velocity field

Fig.5 shows the velocity field of ground deformation. The maximum velocity is found to be near the edge of structure, and decreases towards the far field. The soils below the structure were pushed downward and flow to the two sides. In general, lager velocity was found at the first 10seconds, after which it significantly decreased, and it almost became zero at the end of simulation when the buoyancy and viscous drag force were balanced by the structure weight.



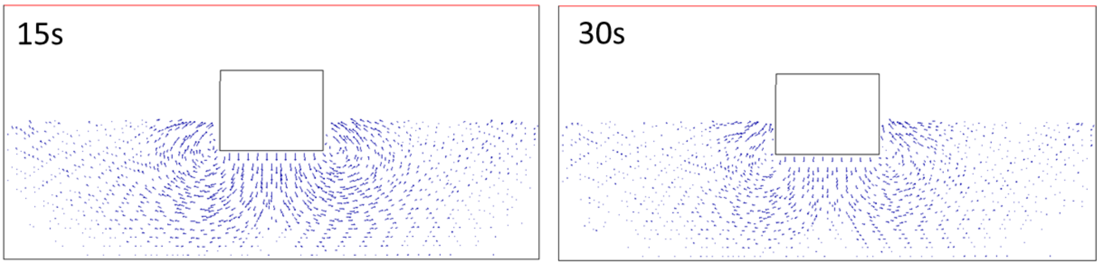


Fig.5 Development of velocity field during structure subsidence

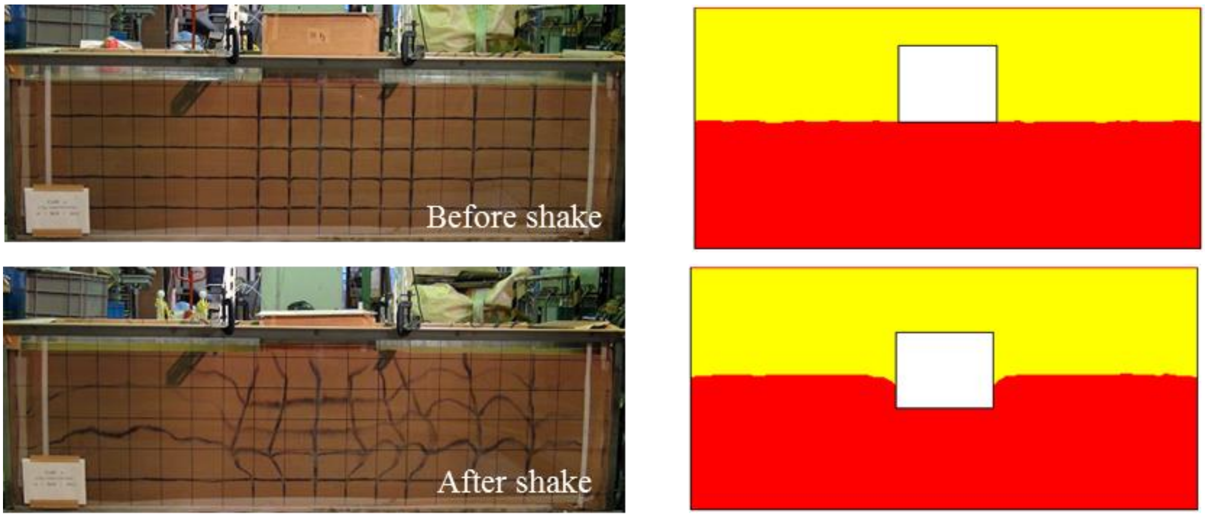


Fig.6 Comparison of experimental and simulation configuration before and after shake

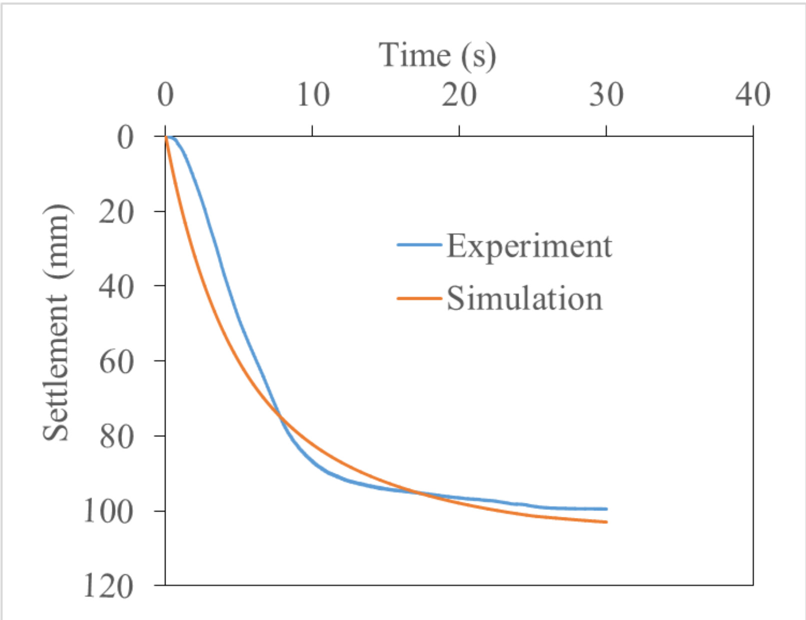


Fig.7 Comparion of total structrue settlement

Structure subsidence

The results of structure settlement before and after shake during shaking table test, together with the results obtained from simulation are shown in Fig.6. Notable settlement can be obervated both from experiment and numerical simulaition, which demonstrates the harmfulness of seimic liquefaction. Fig. 7 show the compariosn of settlement development during the whole process. The overall tendency as well as the ultimate settlement values are in good agreement. The settlement was developed most rapidly within the first 10 seconds of test, and then it turned to become stable. This is also comfirmed by the moving velocity of the structure as shown in Fig. 8. It is found that the settlement increased significnatly at very beginning of liqufaction. The velocity climbed to an peak value within 0.5s and then decreased gradually. It is suggested that the bouyancy force plays a important role after the structure sinked into the liquifed soil.

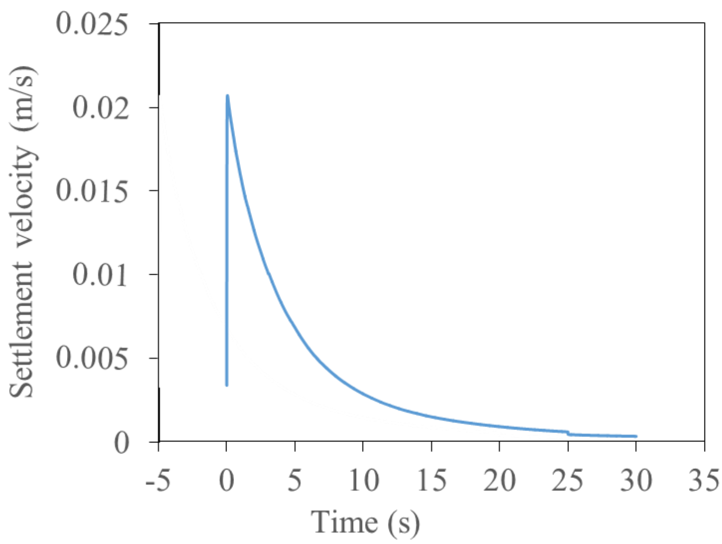


Fig.8 Developtment of settlment velocity of the structrue

Conclusions

Structure settlement is one of main damages observed in liquefaction prone areas. To analysis the settlement behavior of the existing structure. A viscous fluid modelling method with dynamic mesh was used to simulate the process of structure subsidence on liquefied ground. The liquefied ground was modelled as a viscous fluid, the structure was modelled as a moving rigid and the deformed mesh was updated using dynamic mesh.

The proposed method was examined by simulating and comparing with the results obtained from a 1-G shaking table test. It is found that the settlement of structure occurred most rapidly at the very beginning of liquefaction. The settlement behavior from viscous fluid modelling was consist with the measured settlement from shaking table test. It is therefore verified the validity of the proposed method.

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References

[1] Audemard FA, Gomez JC, Tavera HJ, Orihuela N (2005) Soil liquefaction during the Arequipa Mw 8.4, June 23, 2001 earthquake, southern coastal Peru. Eng Geol 78(3–4):237–255.

[2] Huang Y, Jiang XM (2010) Field-observed phenomena of seismic liquefaction and subsidence during the 2008 Wenchuan earthquake in China. Nat Hazards 54(3):839–850

[3] Towhata, I., Maruyama, S., Kasuda, K. I., Koseki, J., Wakamatsu, K., Kiku, H., and Hayashida, T. (2014). Liquefaction in the Kanto region during the 2011 off the pacific coast of Tohoku earthquake. Soils and Foundations, 54(4): 859-873.

[4] Ishihara, K., Araki, K. & Bradley, B., (2011) Characteristics of liquefaction-induced damage in the 2011 great east Japan earthquake. Hanoi, Proc. of International conference on geotechnics for sustainable development, Geotec, Hanoi.
[5] Tokimatsu, K., Tamura, S., Suzuki, H., and Katsumata, K. (2012). Building damage associated with geotechnical problems in the 2011 Tohoku Pacific Earthquake. Soils and Foundations, 52(5): 956-974.
[6] Towhata I, Vargas-Monge W, Orense RP, Yao M (1999) Shaking table tests on subgrade reaction of pipe embedded in sandy liquefied subsoil. Soil Dyn Earthq Eng 18:347–361
[7] Hwang JI, Kim CY, Chung CK, Kim MM (2006) Viscous fluid characteristics of liquefied soils and behavior of piles subjected to flow of liquefied soils. Soil Dyn Earthq Eng 26:313–323.
[8] Dashti, S., Bray, J.D., Pestana, J.M., Riemer, M. and Wilson, D. (2010). Mechanisms of seismically induced settlement of buildings with shallow foundations on liquefiable soil. Journal of Geotechnical and Geoenvironmental Engineering, 136(1):151 – 164.
[9] Uzuoka, R., Yashima, A., Kawakami, T., and Konrad, J. M. (1998). Fluid dynamics based prediction of liquefaction induced lateral spreading. Computers and Geotechnics, 22(3): 243-282.
[10] Hadush, S., Yashima, A., and Uzuoka, R. (2000). Importance of viscous fluid characteristics in liquefaction induced lateral spreading analysis. Computers and Geotechnics, 27(3): 199-224.
[11] Tamate, S., and Towhata, I. (1999). Numerical simulation of ground flow caused by seismic liquefaction. Soil Dynamics and Earthquake Engineering, 18(7): 473-485.
[12] Huang, Y., Mao, W., Zheng, H., and Li, G. (2012). Computational fluid dynamics modeling of post-liquefaction soil flow using the volume of fluid method. Bulletin of Engineering Geology and the Environment, 71(2): 359-366.
[13] Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of computational physics, 39(1), 201-225.
[14] Youngs, D. L. (1982). Time-dependent multi-material flow with large fluid distortion. Numerical methods for fluid dynamics, 24(2), 273-285.